ENGINEERING TRIPOS PART IIB

Thursday 05 May 2011 2.30 to 4

Module 4C3

ELECTRICAL AND NANO MATERIALS

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

There are no attachments to this paper.

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

1 (a) Describe carefully the properties of dielectric materials that determine their classification as either pyroelectric or piezoelectric. Explain the microscopic basis of the pyroelectric and piezoelectric effects that are observed in these materials. Describe briefly the difference between direct and indirect piezoelectric effects. [40%]

(b) Define the current responsivity R_i and voltage responsivity R_v of a pyroelectric detector. Identify the conditions under which a pyroelectric detector operates under current and voltage mode.

The temperature difference ΔT between a pyroelectric element and its surroundings when exposed to incident, sinusoidally modulated radiation, $W = W_0 \, e^{i\omega t}$, is given by;

$$\Delta T = \frac{\eta \; W_0 \; e^{i\omega t}}{G_T + i\,\omega H}$$

where η is the emissivity of the absorbing electrode, G_T is the thermal conductance to the surroundings and H is the thermal capacity. Derive the following expression;

$$|R_i| = \frac{\eta \, p \, A \, \omega}{G_T \sqrt{1 + \omega^2 \tau_T^2}}$$

where p is the pyroelectric coefficient, A is the area of the absorbing electrode and τ_T is the thermal time constant $(= H / G_T)$ of the device. [30%]

(c) Sketch the variation of R_i with ω and state the conditions under which R_i is constant. [10%]

(d) A pyroelectric element is constructed from lithium tantalate ($LiTaO_3$) of thickness 30 μm and absorbing electrode emissivity 0.95. Calculate its current responsivity under the conditions identified in part (c).

Materials constants for $LiTaO_3$ are; $p = 230$ μCm^{-2}K^{-1} and $c = 3.2$ MJm^{-3}K^{-1}. [20%]

2 (a) Describe the physical differences between hard and soft permanent magnet materials and explain how these account for their behaviour in magnetic circuits. [15%]

(b) Sketch the variation of flux density with applied magnetic field at constant temperature over a full field cycle for a hard permanent magnet material and a soft permanent magnet material. Indicate the key parameters of each material on the relevant sketch. [20%]

(c) Explain briefly using B-H sketches how magnet geometry influences the choice of a magnetic material. Give two applications of a hard permanent magnet material and two applications of a soft permanent magnet material. [20%]

(d) Explain briefly how magnetic flux density is generated by a homogeneous bulk type II superconductor, such as Y-Ba-Cu-O (YBCO). Describe how a bulk type II superconductor of slab geometry can be magnetised to generate its maximum trapped field in the plane of the slab. [20%]

(e) Compare the magnetic flux density generated:

(i) at the centre of a 5000 turn cylindrical coil of length 15 cm that carries a current of 5 A;

(ii) at the surface of a long cylinder of YBCO of diameter 2 cm that carries a uniform, field-independent critical current density of 30×10^3 A cm^{-2}.

Indicate briefly the factors that may limit the field generating capacity in each case. [25%]

(TURN OVER

3 (a) Explain the principles of atomic layer deposition. [15%]

(b) The chemical vapour deposition (CVD) process of a thin film at atmospheric pressure is surface-reaction controlled at 700 °C with an activation energy of 2 eV. The deposition rate at this temperature T is 100 nm s^{-1}.

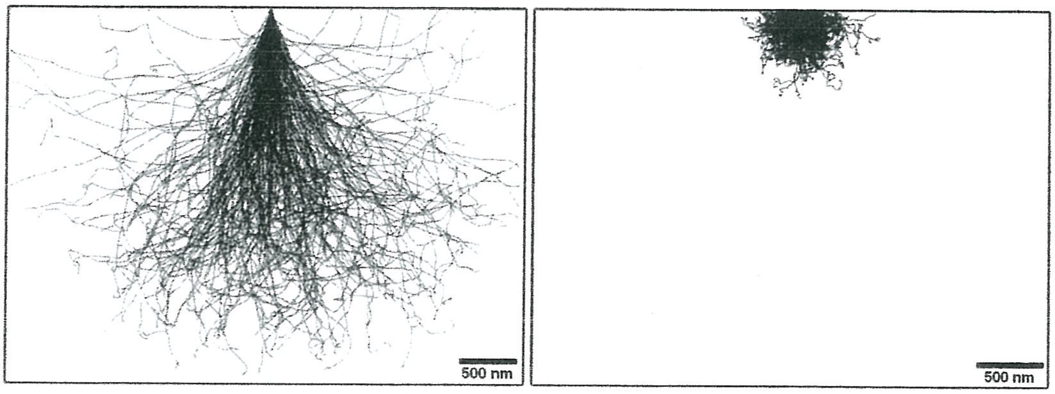
(i) Estimate the deposition rate at 800 °C. [10%]

(ii) Explain why and how the actual deposition rate at 800 °C might differ from the value predicted in part (i). Illustrate your answer with a sketch of the variation of deposition rate with $1/T$ for a typical CVD system. [25%]

(c) Figure 1 shows cross-sections of the simulated trajectories of 20 keV electrons incident normally to substrates of gold and carbon. Identify which cross-section corresponds to which substrate, explaining carefully your reasons. [20%]

(d) Describe the principles of energy dispersive X-ray spectroscopy (EDS) used in a scanning electron microscope (SEM). Explain why voltages of the order of kV are required for EDS, and why electrons with energies at such voltages do relatively little damage to the sample. [20%]

(e) Outline briefly one other technique for analysing the composition of a thin film and state the principle of detection. [10%]



(a) (b)

Fig. 1

4 (a) Describe the advantages and disadvantages of Si, GaAs and GaN for use in various types of semiconductor device, such as computer, opto-electronic and power. [30%]

(b) Explain how band offsets can be used to confine electrons and holes in light-emitting semiconductor heterostructures. [15%]

(c) Explain the mechanism of transfer or modulation doping in a semiconductor heterostructure. What limits the choice of materials? [15%]

(d) Describe the relationship observed between band gap and the size of crystal cell or bond length using diagrams to illustrate your answer, and explain why lattice-matching is important in semiconductor heterostructures. Calculate the density of mismatch dislocations per unit length of two semiconductors of lattice constant d and $d + \delta d$. [40%]

(TURN OVER

5 (a) Explain substitutional and interstitial doping of a semiconductor. Identify the elements used to dope IV and III-V semiconductors. [15%]

(b) The effective mass model, based on a hydrogenic atom, is commonly used to describe the binding energy of donor electrons. The energy levels of the hydrogen atom are given by;

$$R = \frac{e^4 m}{32\,\pi^2 \varepsilon^2\,\hbar^2}$$

where the symbols are defined in lectures.

Carefully explain this model. [30%]

(c) Explain carefully why doping is difficult in some semiconductors, and describe three different mechanisms that can limit doping. Explain which of these are particularly important in the doping of Si, diamond, GaAs and ZnO, and for electrons or holes in HfO_2.

Material	ε_r	m^* electrons	m^* holes	Band gap (eV)
Si	12.0	0.26	0.40	1.10
Diamond	5.7	1.30	0.40	5.50
GaAs	10.9	0.06	0.10	1.45
ZnO	4.0	0.10	4.00	3.40
HfO_2	4.0	1.00	12.00	6.00

[30%]

(d) In insulators, defects produce states below the band edges. Explain how this leads to conduction under high electric fields for the Poole-Frenkel and Fowler-Nordheim conduction mechanisms. [25%]

END OF PAPER